DEVELOPMENT OF MOTORIZED AZIMUTHAL SCANNERS FOR ULTRASONIC NDE OF COMPOSITES

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INTRODUCTION

Composites are a material class for which nondestructive material property characterization is as important as flaw detection. Fiber reinforced composite laminates often possess strong in-plane elastic anisotropy attributable to the specific fiber orientation and layup sequence. Many of these elastic anisotropies may be investigated using ultrasound [1-6], among which angular measurements are often used. Hsu et al [3,4] used angular scan of acousto-ultrasonic signals to investigate fiber reinforced composite laminates. By placing and rotating two contact transducers on the same side of crossed-plied composite laminates, the angular dependence of the acousto-ultrasonic signal was measured and found to have good correlation with the fiber orientation of the sample. Angular measurement of normal-incident shear wave has also been used to detect errors in layup sequence and ply orientation in both green (before cured) and cured composites [4-6]. The transmitted signals of normal incident shear wave in a "crossed polarizer" configuration were found to be particularly sensitive to ply misorientation and layup sequence in a laminate. For green composites, sandwiched between aluminum delay lines, EMATs (electro-meganetic transducer) were used so that the problem of changing coupling condition during the angular scan was avoided. This technique was believed to hold good potential as a practical NDE tool for detecting layup errors during the manufacturing process [5].

In order to develop these methods into practical inspection tools, automation is clearly needed. In this work, we set out to develop motorized azimuthal scanners for different measurement modalities for acquiring ultrasonic signals as a function of in-plane azimuthal angle. The first is a motorized, PC-controlled angular scanner for the acousto-ultrasonic configuration using two contact transducers, and the other is for making transmission measurements using a pair of normal-incidence shear wave EMAT probes. Data acquisition software was developed and the motorized azimuthal scanners were tested on composites with different layups. These two scanners will be used for accelerating the study of fiber orientation and lay-up sequence errors in both green laminates and cured composite panels.

MOTORIZED AZIMUTHAL CONTACT MODE SCANNER

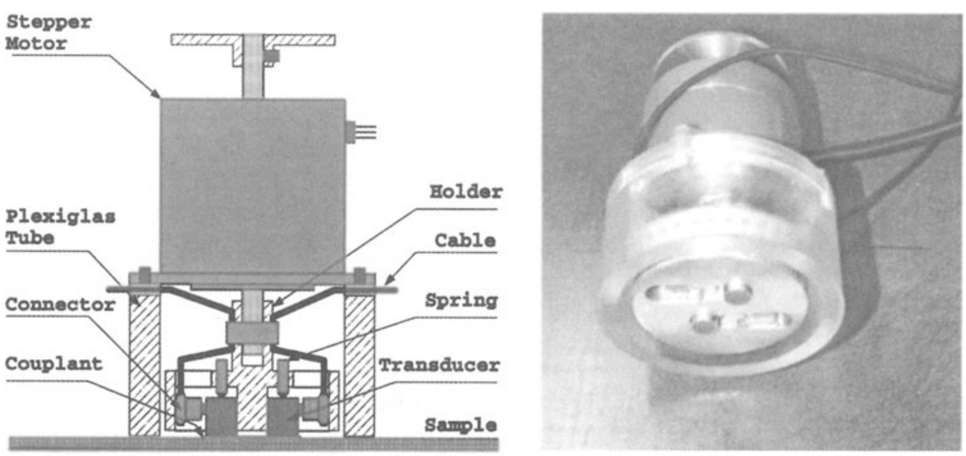
System Design

A schematic diagram of the motorized azimuthal contact mode scanner is shown in Fig. 1(a). Two 5MHz, 1/4 inch diameter contact mode longitudinal transducers, one of which serves as a transmitter and the other a receiver, are used in an acousto-ultrasonic configuration. The transducers are closely placed (0.75 inch separation) so that enough signal could be received and the scanner could be compact. The two transducers are supported by a holder which can be rotated by a stepper motor with a maximum resolution of 0.9 degree. Each time after a full revolution of scan, the scanner reverses to the starting position so that the cables to the transducers will not continue to wrap around the axle. Two adjustable small springs are used to maintain a certain pressure on the transducers so that the transducers are kept in contact with the sample during the azimthual scan. Oil couplant can be used for the scan. A photograph of the scanner is given in Fig. 1(b).

Figure 2 shows a photograph of the whole system. The system consists of a PC, a pulser-receiver, a motor driver and the contact mode probes described above. The parallel port of the PC is used to output the motor control signal and a high-speed data acquisition board is used to digitize the acousto-ultrasonic signals. A graphics based user interface software was developed for scan control and data analysis. With the motorized scanner, a typical azimuthal scan (360 degree with a step of 1.8 degree) can be done in less than one minute.

Scan Results and Discussions

An important issue with contact mode measurement is the coupling problem. Contact transducers are usually considered unsuitable for scanning because the coupling condition is hard to maintain constant. To check the coupling condition during an azimuthal scan, the scanner was applied to a plexiglas plate with a thickness of 1.84 mm.



(a) (b)

Fig. 1 The motorized azimuthal contact mode scanner: (a) schematic diagram; (b) photograph.

Fig. 2 A photograph of the motorized azimuthal contact mode scan system showing the PC, pulser-receiver, motor driver and contact mode probe.

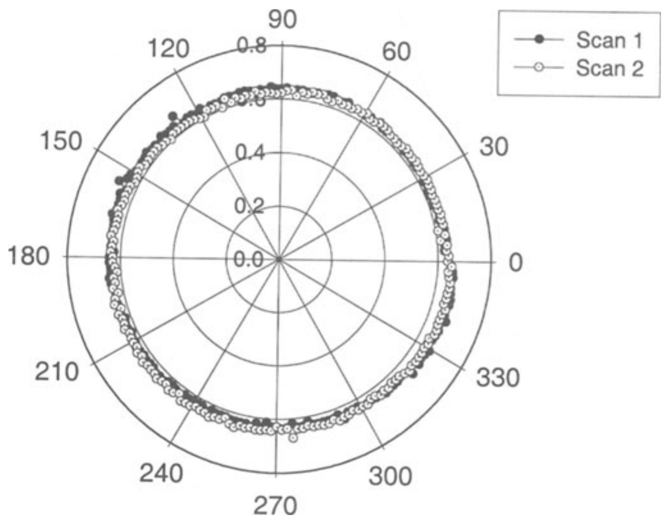


Fig. 3 Azimuthal scan results on a plexiglas plate with a thickness of 1.84mm.

Figure 3 shows a polar plot of the angular dependence of the peak-peak amplitude of the scan signal. Due to the isotropic nature of the sample, a circle was obtained, as expected. The fluctuations, which are mainly caused by the changes of the coupling conditions, are quite small. Because the anisotropy of the composite laminates is usually very strong, the small changes of coupling condition will have little effect on the azimuthal scan results of composite samples.

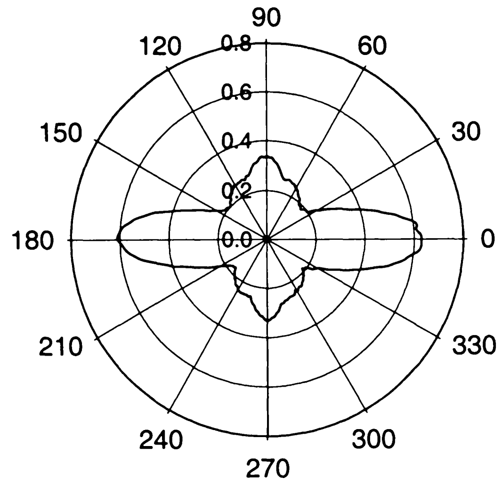


Fig. 4 Azimuthal scan result on a graphite/epoxy composite laminate with a layup of $[(0_3/90)_{25}]$.

The scanner was also tested on crossed-plied composite laminates. Figure 4 shows the azimuthal scan result on a graphite/epoxy composite sample with a layup of $[(0_3/90)_{25}]$. The sample is approximately 0.5 inch thick. It can be seen clearly that the peaks of the acousto-ultrasonic signal appear along the fiber directions and the peaks along 0° are much stronger than those along 90°, due to the fact that there are more fibers along 0° direction. The scan result can therefore be used to check the layup of laminates.

For laminates with complex layups, the scanner was also applied; however, the correlation between the amplitude of the acousto-ultrasonic signal and the fiber layup was found to be generally not so simple. In such cases, the RF waveforms at each angle may help the study of the composites. With the motorized scanner, this can also be done with ease. Figure 5 presents a full waveform display of the azimuthal scan for a carbon/bismalyimide sample. A theoretical model is needed for the interpretation of the azimuthal scan results on laminates with general layups.

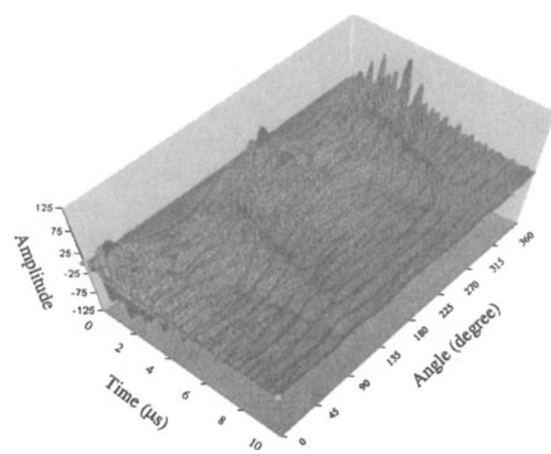


Fig. 5 Full waveform display of an azimuthal scan on a 16-ply (8@0°, 4@45°, 4@-45°) carbon/bismalyimide sample.

MOTORIZED AZIMUTHAL EMAT SCANNER

System Design

A schematic diagram of the EMAT scanner is shown in Fig. 6(a). Two stepper motors are used to rotate the EMATs (1.8"×1.5"×0.75") simultaneously. The aluminum blocks were used to support the motors and to hold and apply pressure on the sample. The aluminum blocks also provide conducting surfaces on which the EMAT can generate and detect the shear waves and serve as an acoustic delay line, which is required by the EMAT receiving system used. For cured composite laminates, a shear couplant is needed between the sample and the aluminum blocks. In the case of green laminates, no couplant is needed and the shear wave can be detected effectively via the pressure applied on the sample between aluminum blocks. Under computer control, the azimuthal scan can be performed either "aligned" (with EMATs parallel to each other) or "crossed" (with EMATs perpendicular to each other). The crossed scan is very sensitive to ply misorientation in the sample while the aligned scan serves as a references with which the amplitude of the crossed scan can be compared to. The computer control and data acquisition system used is the same as that of the azimuthal contact mode scanner except that the computer now controls two stepper motors. It was found in tests that the current in the stepper motors produced noises greater than the received signal. To avoid this problem, the currents in both motors are momentarily turned off after the motors get to each new position so that the signals are always acquired without the motor noises. A photo of the EMAT scanner is shown in Fig. 6(b).

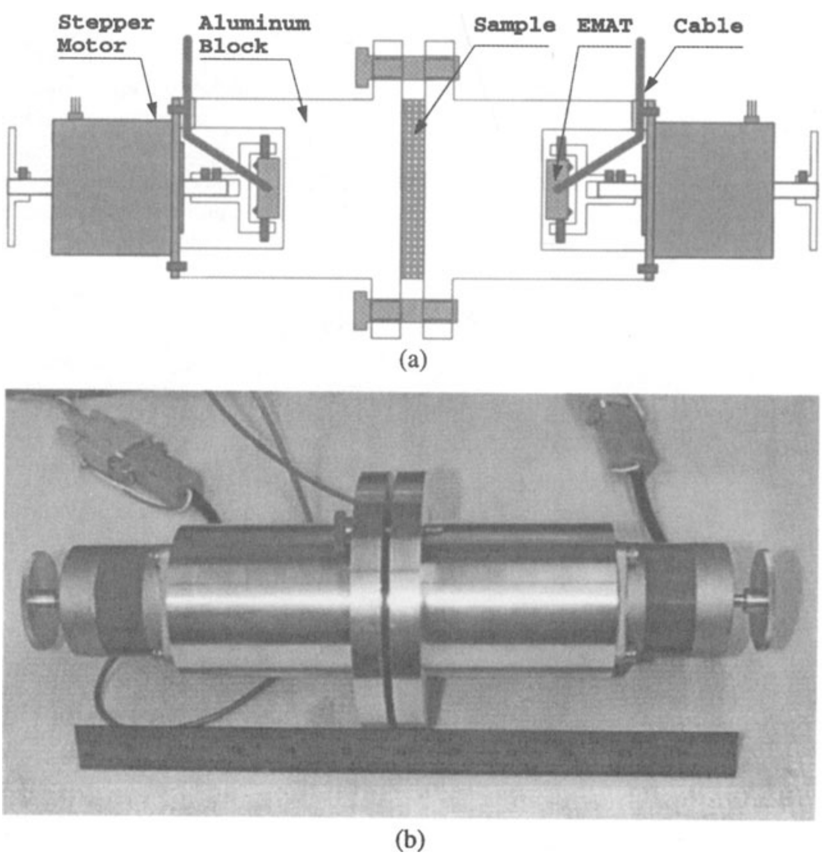


Fig. 6 The motorized azimuthal EMAT scanner: (a)schematic diagram; (b) photograph.

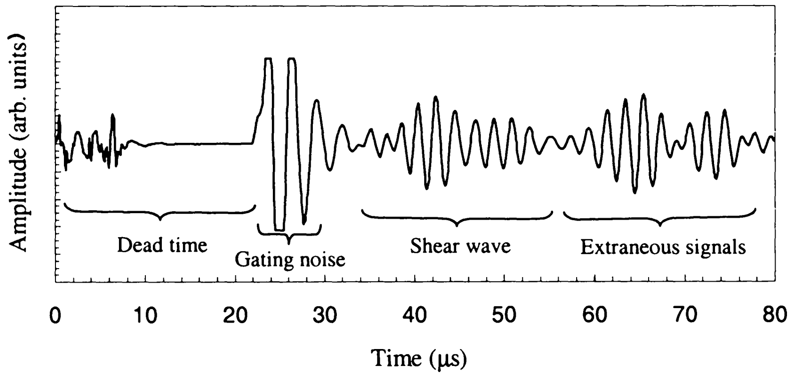


Fig. 7 Shear transmission waveform through a 24-ply unidirectional graphite-epoxy laminate with both EMATs aligned to the fiber direction.

Scan Results and Discussions

Figure 7 shows a typical waveform during an azimuthal EMAT scan. The waveform was acquired on a 24-ply unidirectional graphite epoxy composite sample with both EMATs placed at 0 degree, which is parallel to the fiber direction. The shear wave signal, which follows the gating noise of the system, can be clearly identified. The angular dependence of the peak-peak amplitude of the shear wave is shown in Fig. 8. Figure 8 also gives the crossed scan result and both results are compared to that predicated by the theoretical model. The model treated the composite as a layered structure. In each ply of the composite, the shear wave field was expressed as a summation of four partial waves: two polarized along the fiber propagating up and down and two polarized perpendicular to the fiber propagating up and down. Transfer matrix technique was then used to establish the relationship of the displacement stress vectors at the top and bottom interfaces. Finally the displacement and stress continuity conditions were applied and the transmitted fields were solved. Due to the limitation of space, the details of the model will be presented elsewhere.

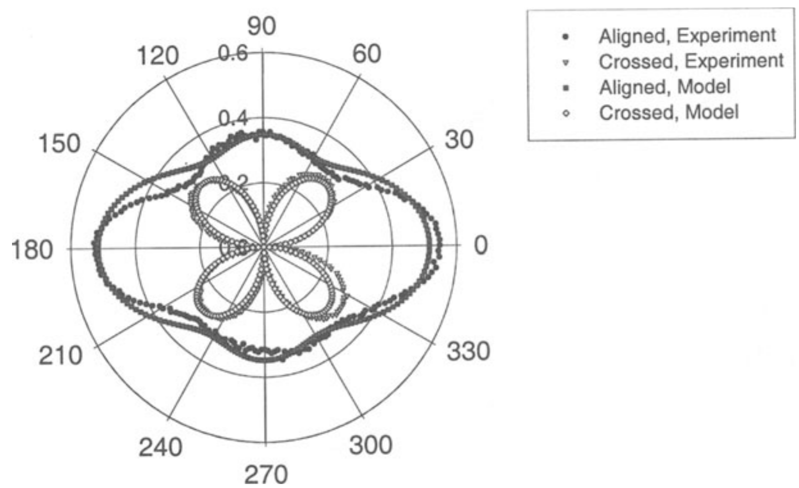


Fig. 8 Angular dependence of the aligned and crossed EMAT shear wave transmission signals through a 24-ply unidirectional graphite-epoxy laminate.

It can be seen from Fig. 8 that the agreement between the experiment and theoretical model is satisfactory. The aligned scan result shows a distorted elliptical shape instead of a near circle. This is due to the angular dependent reflection and transmission coefficients between the aluminum and the sample. Because aluminum is isotropic and the composite is anisotropic, the transmitted signal is angular dependent. In general the scan result will be a combination of the contributions of both aluminum-composite interfaces and the sample itself. The output of a shear wave scan is mainly determined by the phase difference of the transmitted partial waves. For most layups, this phase difference is nearly zero at low frequency. Therefore the aligned scan will show a large elliptical shape while the crossed scan will show a smaller pattern whose shape is determined by the layup.

When one or more plies in the sample are misoriented, the resultant phase change will show up clearly as a change of pattern in the crossed scan results. The motorized EMAT scanner is being applied to the test of green composites with complex layups.

CONCLUSIONS

Two motorized, PC-controlled ultrasonic azimuthal scanners, one for contact mode in the acousto-ultrasonic configuration and the other for EMAT-generated shear wave transmission method, have been designed and built for NDE of anisotropic composite plates. The contact mode motorized scanner has been used to determine the fiber orientation on graphite epoxy laminates. The motorized EMAT scanner has been tested on unidirectional graphite epoxy laminate and a good agreement between the experiment and model was obtained. Further work includes developing theoretical model for the contact mode measurement, applying motorized contact mode scanner on various types of composites with different layup sequences and porosity contents, applying EMAT scanner on green laminates with different layups and investigating its possible application in composite manufacturing process.

ACKNOWLEDGEMENT

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